



Light Duty NGV Direct Injection Discussion

Challenges & Approaches

Natural Gas Vehicle Technology Forum 2014 Meeting

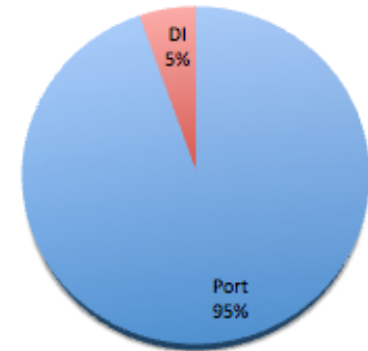
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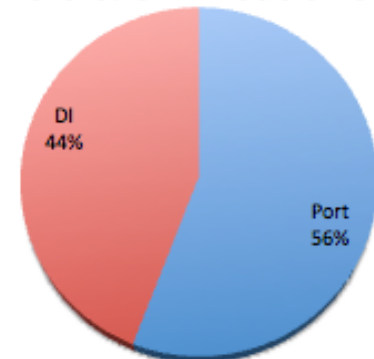
Increasing Prevalence

- Direct Injection (DI) methods provide combustion efficiencies vs. Port Injection (PFI)
 - Leaner fuel mixtures
 - Higher fuel economy
 - Higher power output per engine liter
 - More precise fuel control
 - Lower CO, NOx, HC emissions
- New Vehicle Ford & GM*
CARB Executive Order Review
 - Model year 2009: 5 of 92 models were DI
 - Model year 2014: 34 of 77 models were DI

Ford & GM Models 2009



Ford & GM Models 2014



* Ford & GM represent most all base vehicles for light duty CNG fuel conversions in the USA.



OEM Accommodation for NGVs



QVM gaseous fuel prepped engines all PFI

Represents less than 1% of vehicle sales yet retains strong corporate support for now

2015 bi-fuel Impala 3.6L DI engine modified for PFI

Current 6L engine offerings PFI (trucks, vans)

International NGV markets also PFI (i.e. Opel Zafira)



DI Engines – NGV Technical Progression

Direct Injection

Technical pathway for Direct Injection CNG.



Non-critical as market can persist as PFI, but value in R&D needed to identify solution for dedicated CNG DI. Reliance of PFI only may incur FE limit.

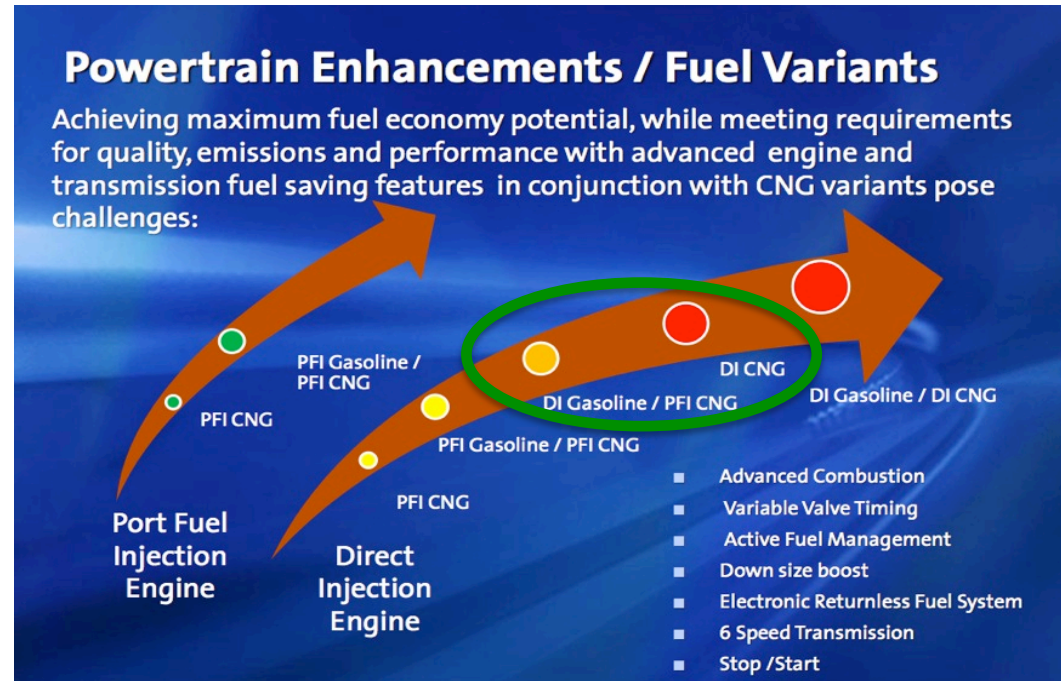
Bi-fuel DI Gasoline / PFI CNG systems are appearing:

OEM (Europe):

VW Passat EcoFuel

Aftermarket:

ANGA showcase vehicles



Above: from 2013 NGVTF – Dick Kauling, General Motors
(emphasis added in green)



Next Horizon: Direct Injected CNG

- Positives:
 - Higher compression ratio more closely aligned for natural gas properties (11:1 to 12:1 typical)
 - Cylinder heads, seats, valves generally compatible for natural gas
 - Holds promise of improvements such as gained by gasoline with DI (fuel economy, performance, emissions)
 - HP fuel injection premise irrelevant as natural gas is already atomized
- Challenges for Gaseous Fuel:
 - Readily-available gaseous fuel injectors not designed for high pressure injection, nor pressure and heat from combustion chamber
 - Even if HP injectors were available, required pressures severely limit range
 - Significant control strategy modifications:
 - Injection timing events
 - Liquid fuel pump disable / enable
 - OBD monitors



Approach #1:

Maintain High Pressure (HPDI)

Gas booster (hydraulic intensifier) on vehicle
maintains 4200 psi injection pressure as CNG is consumed



Commercialized in Australia by iGas Energy for
Westport HPDI 15 liter engine running on CNG



Good solution for heavy duty diesel cycle vehicles
Negligible incremental power requirement
Provides up to 90% onboard fuel utilization

Approach likely infeasible for light duty otto cycle:
weight & space claim
energy loss
thermal effects
component costs / additional complexity
high pressure injector development



Photos courtesy
iGas Operations Pty Ltd
www.iGasEnergy.com



Approach #2:

Low Pressure Direct Injection (LPDI)



Patent-pending method developed by
NGV veteran
Kevin Fern, President
Crazy Diamond Performance, Inc.
Shelby Township, Michigan

Injector Interface Device (IID) interposed between fuel rail and combustion chamber

IID valve opens to provide injection windows:

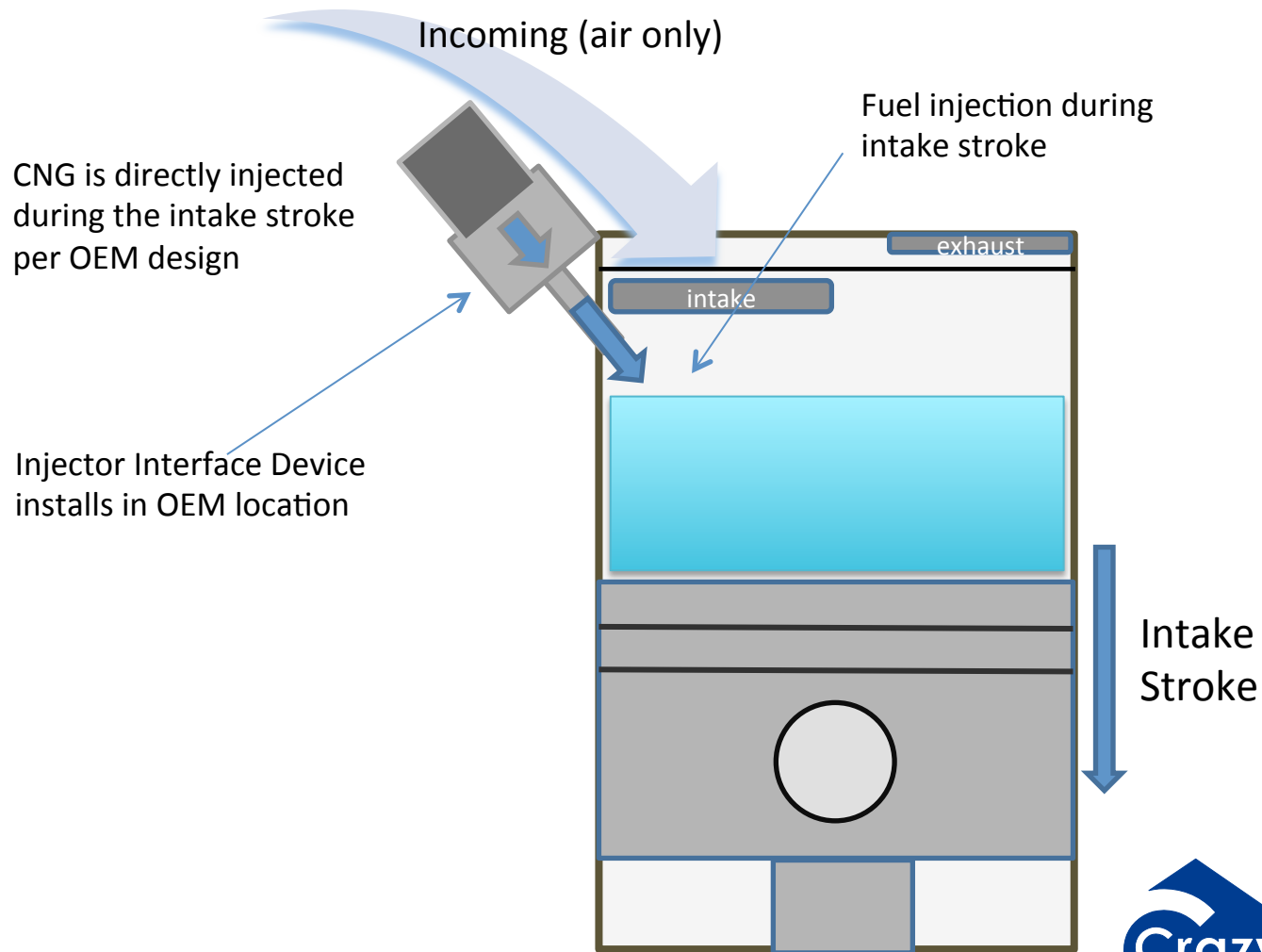
- Entire intake stroke
- Much of compression stroke

IID valve closes to protect injector from combustion pressure:

- Final portion of compression stroke
- Entire power and exhaust strokes



LPDI Sequence: Intake Stroke



LPDI Development Engine

- 2013 GM 2.4L ECOTEC DI four cylinder engine
- 182 HP/172 FTLBS TQ
- 11.5:1 compression
- Variable Valve Timing (VVT)
- Current E-39 ECM



Current State of LPDI Development

- Proof of concept using IID and gaseous fuel injector is complete
- Testing has determined the maximum fuel injector target window and flow requirements
- Engine fuel mapping, ignition timing, engine diagnostics protocols determined
- Engine fuel pressure <300 psi



LPDI Contribution to State of the Art

- Cost Reduction:
 - pressure regulators, etc.
- Does not require the repackaging of engine to suit CNG:
 - Reuses intake manifold, engine control module (ECM)*, wire harnesses
- Ability to inject on both intake and (partial) compression stroke
- No added high pressure components in engine compartment
- Overall power output likely to meet base gasoline engine
 - Removal of parasitic power loss from HP gasoline fuel pump (i.e. off cam shaft)
 - Benefits of higher compression and aggressive timing profile for CNG
- Applicable to any gaseous fuel, in variety of configurations (inline, V)

*Currently testing injector load for functionality



LPDI Development Challenges

- Short injection “on” time – limited window to inject fuel
- Design limitations of the low pressure fuel injector
 - Adequate flow vs. cycle time
 - Adequate resistance to thermal effects & combustion cycle pressure
- Controls:
 - Use of OEM ECM to control injection pulse vs. add-on controller
 - OBD monitoring of IID
- Durability testing of IID
- Integration of injector design is eventual outcome

